12th IEA Heat Pump Conference 2017

Flexibility offered by residential floor heating in a smart grid context: the role of heat pumps and renewable energy sources in optimization towards different objectives.

Annelies Vandermeulen[a,b,*], Luckas Vandeplas[a], Dieter Patteeuw[a,b], Maarten Sourbron[a], Lieve Helsen[a,b]

[a]KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300 box 2421, 3001 Leuven, Belgium
[b] EnergyVille, Thor Park, Waterschei, 3600 Genk, Belgium

Abstract

The increasing share of renewable energy sources (RES) in the electricity generation mix turns grid balancing into a real challenge due to the intermittent character of RES. Thermal energy storage (TES) can provide flexibility to shift electricity use in time and can contribute to grid balancing. Residential floor heating systems typically combined with a heat pump can be used in this context by storing thermal energy within the floor. This paper assesses the flexibility a floor heating system can provide when controlled by a model predictive controller (MPC), through scenario analysis. MPC formulations with different objectives, such as maximising the renewable energy fraction in provided electricity, are compared. The scenario analysis includes two nearly zero-energy buildings (NZEB) and also compares an air-water heat pump with an electric resistance heater. Besides the current RES share, which amounts to about 12% of total electricity production in Belgium, a few future scenarios assuming a share of 40% RES are analysed as well. The results show that a maximisation of RES is only beneficial in the future scenario, otherwise the increase in energy use is too high to be interesting. Moreover, a more realistic primary energy factor (PEF) between 2.1 and 2.25 is determined for the Belgian context. The PEF is used in energy efficiency calculations of buildings and is currently assumed to be 2.5 in Europe.

Selection and/or peer-review under responsibility of the organizers of the 12th IEA Heat Pump Conference 2017.

Keywords: Smart grids, Floor heating, Flexibility, Renewable energy sources, Heat pump, Primary energy factor

* Corresponding author. Tel.: +32 16 37 75 28 .
E-mail address: annelies.vandermeulen@energyville.be.

1. Introduction

Renewable energy sources (RES) should produce at least 27% of the used electricity in Europe by 2030 [1]. An important means of reaching this goal is the use of wind and solar energy. However, both wind and solar energy are intermittent and their increasing share on the electricity grid could cause balancing problems. One of the proposed solutions is demand side management (DSM). The goal of DSM is to incentivise the electricity consumer to adapt his or her electricity consumption to aid in keeping the grid balanced. When this happens in the context of a smart grid, an extensive communication network can be used that sends signals about the current situation of the electricity grid. These signals can for example be the real-time price of electricity [2], the optimal load profile [3] or the current and expected share of renewable energy on the electricity grid. Based on these signals the consumer can adapt his or her consumption profile by using the flexibility provided by thermal energy storage (TES).

This potential of TES in buildings has already been thoroughly studied in different configurations: concrete core activation [4]–[6], domestic hot water tanks [7]–[10] and floor heating systems [11]. An overview of these and other thermal storage possibilities was made by Arteconi, Hewitt and Polonara [12]. These studies clearly show TES is capable of contributing to DSM. This paper focuses on a floor heating system in residential buildings, in which the possibility of TES is provided by the large thermal inertia of the screed. This large thermal inertia can provide the flexibility to shift the heat production in time while maintaining thermal comfort of the residents. If the building is heated by a heat pump, the electricity use can hence be shifted in time, to periods with plenty of RES delivering electricity to the grid.

To be able to control the heating system in such a way that it adapts its electricity use to the state of the electricity production, an advanced controller is required. In this paper, a model predictive controller (MPC) is used. The MPC allows optimising towards different objectives, e.g. minimum energy use, minimum heating cost or maximum share of renewable energy in the used electricity. The MPC has, for instance, already been used in previous research to reduce energy use and energy costs in buildings [6], [13]–[15]. These studies confirm model predictive control can reach a reduction in energy use and cost of about 15 to 20% compared to classic controllers, such as a rule-based controller (RBC) using a conventional heating curve.

The goal of this paper is to determine which objectives, and along with that, which signals, can increase the use of electricity originating from RES without increasing the energy use too much. This happens through scenario analysis of residential floor heating in a smart grid context. Furthermore, the results obtained by using an air-water heat pump are compared to a reference case where an electric resistance heater is used. Finally, a more realistic primary energy factor (PEF) is sought, as the current PEF is deemed too high, leading to unjustified disadvantages for heat pumps.

This paper consists of the following parts: Section 2 elaborates on the approach used, Section 3 gives an overview and discussion of the results obtained and, finally, Section 4 summarizes the conclusions.

2. System and methodology

This section describes the method of research. First, Section 2.1 elaborates on the system that is treated. Section 2.2 describes the set-up of the simulations, Sections 2.3, 2.4 and 2.5 discuss, respectively, the models of the buildings, the heating systems and the controllers. Finally, Section 2.6 gives an overview of the full scenario analysis.

2.1 System description

The system analysed in this paper consists of a residential building. This building is equipped with a floor heating system and a domestic hot water (DHW) tank. It is the goal of the controller to ensure that (1) the thermal comfort demands of the residents are met and (2) the residents have access to DHW at 50 to 55ºC at every moment. To this end, heating systems are installed. In this paper, either an air-water heat pump or an electric resistance heater (serving as reference) is implemented in the building. Both these heating systems are electrical devices and hence provide a link with the electrical grid. This link can be exploited by a smart controller to help, for instance, balance electricity production and demand.

2.2 Simulation set-up

The scenario analysis consists of simulations of an MPC controlling the heating system (heat pump or electric resistance) in one of the residential buildings. The exact configuration of the simulation setup, shown in Figure 1, uses a coupling between Modelica (for emulation) and Matlab (for optimisation). The simulation is initialised by simulating a detailed building model in Modelica for one hour. From this simulation, the final states of the building can be extracted, i.e. the temperatures within the rooms, walls and floors at the end of the simulated hour. Matlab then receives this current state of the building and uses this to solve an optimal control problem for the prediction horizon of n hours. To this end it needs forecasts of, amongst others, the weather during the hours 1 till n. The result of this optimisation is the optimal heating profile for the entire horizon. The post-processing converts the first hour of this heating profile to control signals that can be sent to the heating system in Modelica. The building model is then again simulated for the subsequent hour. The resulting new state of the building can again be sent to Matlab and the process can be repeated.

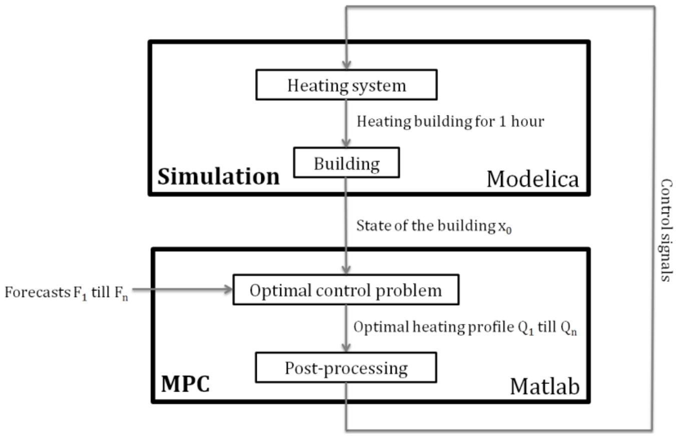

Fig. 1. The different steps in the simulation of the building and the model predictive controller.

2.3 Buildings

The scenario analysis includes two buildings. These buildings were selected to represent average small residential buildings in Belgium, hence a terraced house and a detached house are chosen. These buildings are based on the EPICOOL buildings [8], however small modifications were needed for simple implementation in Modelica and to adjust the thermal insulation towards NZEB. Two models are made of each of these buildings. One is an extensive emulator model, that will receive the control signals generated by the MPC. The second model is a simplified model that is used by the MPC to generate the control signals, as discussed in Section 2.5.

The emulator model is made by using the IDEAS library in Modelica [16]. This model is a multi-zone model in which the heat transfer is modelled with the help of extensive RC-models and which also includes the non-linear behaviour of radiation, absorption and transmission through glazing and convective heat transfer [17].

The second building model is a linearised model in the form of a state-space model. The linearisation algorithm of Modelica, adapted by Picard, Jorissen and Helsen [17], allows directly generating the state-space matrices A, B, C and D, based on the detailed model in Modelica. The structure of the resulting linearised model is shown in Equation 1. In this equation, the vector $\boldsymbol{x}_\mathbf{i}$ is the vector filled with the states of the building at time i. The inputs of the state-space model consist of $T_{ws,j,i}$, the water supply temperature of the floor heating system in room j at time i and $\boldsymbol{u}_\mathrm{i}$, the vector filled with external inputs, such as ambient temperature, solar radiation, wind speeds... The outputs of the state-space model are $T_{z,j,i}$, the room temperatures in room j at time i and $Q_{FH,j,i}$, the heat flowing from the floor heating system to room j during time interval Δt corresponding to time step i. $Q_{FH,j,i}$ can be considered as an output of the state-space model as $T_{ws,j,i}$, which is an input of the model, already determines the heat transfer to the room. By selecting the heat from the floor heating system to the room as an extra output, the required power of the heating system can be determined, as shown below in Equations 2 till 5.

$$\boldsymbol{x}_{i+1} = A\,\boldsymbol{x}_i + B\begin{bmatrix} T_{ws,1,i} \\ \vdots \\ T_{ws,n_{rooms},i} \\ \boldsymbol{u}_i \end{bmatrix} \qquad \begin{bmatrix} T_{z,1,i} \\ \vdots \\ T_{z,n_{rooms},i} \\ Q_{FH,1,i} \\ \vdots \\ Q_{FH,n_{rooms},i} \end{bmatrix} = C\boldsymbol{x}_i + D\begin{bmatrix} T_{ws,1,i} \\ \vdots \\ T_{ws,n_{rooms},i} \\ \boldsymbol{u}_i \end{bmatrix} \tag{1}$$

2.4 Heating systems

The buildings are equipped with a heating system responsible for space heating and DHW preparation. Two different heating systems are investigated: an air-water heat pump (AW-HP) and an electric resistance heater (ERH) acting as a reference. Analogously to the case of the buildings two models are made: an extensive emulator model, based on the IDEAS library and a simple linear model that is used by the MPC. The extensive model includes a detailed model of either the heat pump or the electric resistance heater, the hydraulic circuit and a detailed model of a stratified DHW tank [18]. The heat pump model in this detailed model is based on linear interpolation in performance maps (using condenser temperature, evaporator temperature and modulation level as parameters), as provided by the manufacturer. The heat pump has a nominal coefficient of performance (COP) of 3.17 at 2/35 °C and 2.44 at 2/45°C test conditions (i.e. air/water temperature) for full load operation [19], [20].

The simple linear model only includes a simple model of the heat pump and of a fully mixed DHW tank, as shown in Equations 2 till 5. To ensure the optimal control problem of the MPC remains linear, the COP of the heat pump is assumed to be independent of the condenser temperature. This entails a rather large simplification, as the floor heating system requires much lower temperatures than the DHW preparation. Extra research should be done to assess the exact influence of this simplification on the operation of the MPC and the heat pump.

$$P_{min} \cdot x_{HP,i} \le P_i \le P_{max} \cdot x_{HP,i} \tag{2}$$

$$COP \cdot P_{HP,i} = \sum_{j=1}^{n_{rooms}} \dot{Q}_{FH,j,i} + \dot{Q}_{DHW,i} \tag{3}$$

$$x_{HP,i} = \{0,1\} \quad (4)$$

$$T_{DHW,i+1} = T_{DHW,i} + \frac{1}{\rho c_{p,w} V_{DHW}} \left(- \dot{Q}_{loss,i} - \dot{Q}_{user,i} + \dot{Q}_{DHW,i}\right) \Delta t \quad (5)$$

with P the electrical power of the heat pump, which is assumed to have a minimum modulation of 30%. $\dot{Q}_{FH,j,i}$ is the heat delivered to room j and $\dot{Q}_{DHW,i}$ the heat delivered to the DHW tank at time i. $x_{HP,i}$ is an integer indicating whether the heat pump is on or off. The model of the electric resistance heater has a similar structure, however, instead of a COP, a constant efficiency of 98% is used to describe the relation between the ingoing electricity and the outgoing heat. These constraints, describing the behaviour of the heating system, are based on the work of Patteeuw [21].

The model of the fully mixed DHW tank described in Equation 5 includes the uniform temperature of the tank $T_{DHW,i}$. ρ and $c_{p,w}$ are respectively the density and the heat capacity of water. Three heat flows in and out of the tank are taken into account: (1) losses to the surroundings $\dot{Q}_{loss}$, (2) heat required by the residents $\dot{Q}_{user}$ and (3) the heat provided by the heating system $\dot{Q}_{DHW}$.

2.5 Controllers

This section further elaborates on the two controllers used in the scenario analysis: the MPC framework and the RBC used as a reference. Firstly, this section explains the structure of the optimal control problem to be solved by the MPC. Secondly, the post-processing is discussed which converts the results of the optimal control problem to control signals for the heating system. Thirdly, the RBC that acts as a reference is shortly described.

An optimal control problem is an optimisation in which the control of a specific system is determined such that a chosen objective is minimised. In this case, the MPC solves such a problem to determine the heating profile that, for example, minimises energy use. An optimal control problem consists of two main parts: (1) the objective and (2) the constraints. The structure of the MPC objective used in this research is presented by Equation 6.

$$Obj = \sum_{i=1}^{n} \alpha_i E_i \quad (6)$$

with E_i the electricity used in kWh by the electric heating device, i.e. by a heat pump or an electric resistance heater. i is the time step and n is the time horizon of the optimal control problem. The factor α_i depends on the objective that is used. For example, in case of an energy cost minimisation, α_i is the cost of electricity per kWh during time interval Δt corresponding to time step i. Other objectives have an analogue structure, with the values of α_i depending on the chosen objective.

The second part of the optimal control problem consists of the constraints, which are as follows:

- The state-space model of the building to be heated (see Equation 1) which represents the dynamic behaviour of the building.
- The characteristics and limitations of each heating system as represented by Equations 2 till 5. To ensure a linear optimal control problem, the MPC assumes the COP is independent of the condenser temperature.
- The constraints ensuring that at every moment DHW at 50 to 55ºC is available to the residents.

- The constraints ensuring thermal comfort demands of the occupants are met. The MPC considers thermal comfort is achieved when temperatures remain inside a comfort zone. These comfort zones depend on the type of room and are based on the work of Peeters et al. [22]. There is, however, an allowed daily thermal discomfort that is based on the Standard ISO7730 [23], which prescribes a yearly allowed discomfort of 100Kh. A last restriction on the temperatures set by thermal comfort is a limitation of the maximum temperature of the floor heating surface (32°C in case of a bathroom, 29°C in all other cases) as prescribed by Vasco [24].

The solution of the optimal control problem describes the optimal heating profile. However, this heating profile still needs to be converted to signals that can be sent to the heating system. This is done by the post-processing. By using Equations 1 till 5, the optimal control problem calculates the heat and temperatures to be delivered to each room. However, the heat production system works with only one temperature set point. Therefore the highest temperature set point to send to the rooms is taken. The mass flow rate sent to each of the rooms is then controlled in such a way that the correct amount of heat is delivered. However, the DHW tank is always given priority. Hence when it requires heating, the space heating is turned off.

Besides an MPC, a heating curve base RBC is used as a reference [5]. Using the heating curve, the RBC decides the required temperature of the water in the floor heating system, based on the outdoor temperature. The slope and the offset of this heating curve is determined by considering a steady state energy balance of the building:

$$(UA)_{FH,j}\left(T_{ws,j} - T_{z,j}\right) = (UA)_{z,j}\left(T_{z,j} - T_{amb}\right) \tag{7}$$

with $(UA)_{FH,j}$ describing the heat transfer from the floor heating system to room j and $(UA)_{z,j}$ describing the heat transfer from the room to the surroundings. $T_{ws,j}$ is the water supply temperature of the floor heating system in room j, $T_{z,j}$ the desired temperature of the room and T_{amb} the ambient temperature. This results in the following heating curve:

$$T_{ws,j} = T_{z,j} + \frac{(UA)_{z,j}}{(UA)_{FH,j}}\left(T_{z,j} - T_{amb}\right) \tag{8}$$

Based on this curve, the RBC can decide what temperatures to send to each room. The DHW tank is heated when the temperature at the bottom of the tank falls below a certain temperature and is given priority over the space heating.

2.6 Overview of the scenario analysis

The scenario analysis consists of different variable parameters. Some of these, like the building, the heating system and the type of controllers were discussed in previous sections. Besides these, there are still some other parameters:

- *The MPC objective*: The factor α_i in the objective of the MPC, shown in Equation 6, is varied. This way, different objectives and their results can be compared. The different objectives are listed in Table 1 and are from now on referred to by the names indicated in the table.
- *The simulated period*: four different weeks are chosen, each of them is different with respect to the mean outdoor temperature or the mean share of renewable energy on the grid. There are two cold and two warmer winter weeks. Each pair of weeks has one week with a high share of renewable energy and one

with a low share of renewable energy. The most important results are verified and confirmed by simulations for the entire heating season, from the first of October till the first of May.

- *The share of renewable energy*: a distinction is made between the present day situation in Belgium characterized by approximately 12% of total electricity use originating from RES and a future scenario with an increased renewable energy share of 40%. In this future scenario, two possible efficiencies of the non-renewable electricity production are taken into account: 50% and 60%.

Table 2 gives an overview of all possible scenarios and the way they are referred to in the remainder of the text. The periods are named using the first day of that period, for instance, the period 18/01 is the week starting on the 18th of January.

Each of the simulations uses historic weather data from the years 2014 and 2015 from Uccle, Belgium. The MPC uses historic day-ahead electricity prices from BELPEX for the *Min Cost* objective. The *Max RES*, *Min CO_2* and *Min PE* objectives use electricity generation data from Elia, the Belgian transmission system operator. These generation mix data allow calculating the share of RES in providing electricity, the CO_2-emissions and the PEF for every hour. As historic data is used, the MPC uses perfect predictions, which will cause the results obtained in this research to be rather optimistic.

Table 1. The name and description of the different MPC objectives

Name	Description
Min Energy	Minimising the amount of electricity used to heat the building.
Min Cost	Minimising the operation cost of heating the building.
Max RES	Maximising the use of renewable energy from the electricity grid, used for heating the building.
Min CO_2	Minimising the CO_2 produced when heating the building, taking into account the CO_2 produced by electrical power plants.
Min PE	Minimising the primary energy required to heat the building, with the PEF variable and dependent on the power plants in operation.

Table 2. Overview of the variables that are varied in the simulations.

Building	Heating system	Objective	Periods	Share of RES
		Min Energy	18/01	Current situation: 12% RES
Detached house	AW-HP	*Max RES*	01/02	40% RES with 50% efficiency for non-RES electricity generation
Terraced house	ERH	*Min Cost*	29/03	
		Min CO_2	29/10	40% RES with 60% efficiency for non-RES electricity generation
		Min PE	Entire heating season	

3. Results and discussion

The scenario analysis, for which the variations are summarized in Table 2, allows studying the influence each objective has on the performance of the MPC and its use of (renewable) energy. Firstly, the influence of the different objectives on the use of renewable energy is analysed both in the current scenario and future scenario, with a RES share in electricity of 12% and 40% respectively. Secondly, a comparison is made between the air-water heat pump and the electric resistance heater with respect to the share of renewable energy. Thirdly, an estimation of the primary energy factor is made and finally, the remainder of the variations in Table 2 is shortly discussed.

3.1. Increasing the share of renewable energy

This section investigates which objectives succeed in increasing the renewable energy use. Figure 2 gives the total electricity use for the different objectives (and RBC for comparison) and the share of electricity use originating from RES. It is clear *Min Energy* uses the least electricity together with *Min PE*, while *Max RES* is able to obtain the highest share of renewable energy, but it also increases the electricity use the most. The cost signal (based on the day-ahead electricity wholesale price), on the other hand, does not appear to be a good incentive to increase the share of renewable energy. This day-ahead electricity wholesale price is, amongst others, based on predictions of the renewable electricity production for the next day, and thus suffers from prediction errors, whereas *Max RES* uses historical data, and therefore, perfect predictions. As a consequence, a more interesting price signal to increase renewable energy use would be the intraday electricity price, as this is more heavily influenced by changes in the production of electricity by RES and is adapted during the day to the actual electricity production.

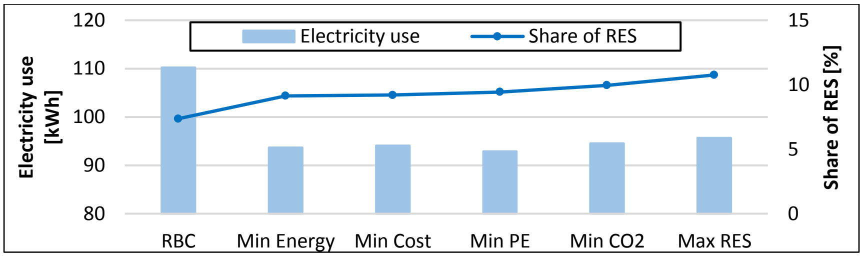

Fig. 2. Comparison of the electricity use and share of the electricity originating from RES, between the different MPC objectives and RBC (see Table 1 for an explanation of the different terms). This is done for the AW-HP in the detached house. The given values are averaged over the four simulated weeks.

Although the share of electricity originating from RES, as show in Figure 2, gives some idea of the increase of the RES use, it is important to look at the absolute differences too. Figure 3 compares the absolute difference in RES use with the absolute difference in total electricity use between *Max RES* and *Min Energy*. In the current situation (12% RES), the increase in total electricity use is 10% higher than the increase in renewable energy use, when using *Max RES*. This is a negative effect since also the net electricity use originating from non-renewable sources rises.

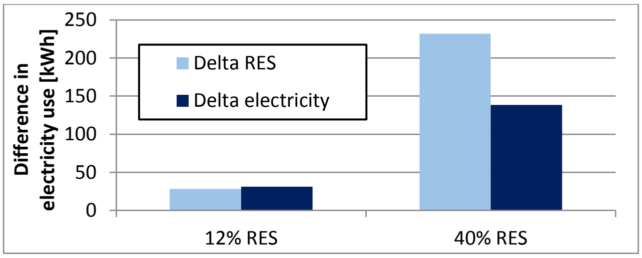

Fig. 3. Comparison of the used renewable electricity (Delta RES) and the used total electricity (Delta Electricity) between *Max RES* and *Min Energy* for the current (12% RES) and future scenario (40% RES). When positive, *Max RES* uses more (renewable) electricity than *Min Energy*. Values apply to the AW-HP in the terraced house, operating during the entire heating season.

This picture changes in the future scenario with 40% of the electricity generated by RES, which is also shown in Figure 3. In this case, the absolute increase in renewable energy is much larger than the increase in total electricity use. This means the increase in renewable energy use completely compensates the increase in electricity use. Therefore, *Max RES* is not only capable of using more renewable energy, but can also reduce the use of non-renewable energy. However, this increase in energy use causes an extra energy cost for the consumer of approximately 9% for an entire heating season compared to *Min Energy*. To ensure consumers want to participate in demand side management the gains should be larger than the costs and incentives should be provided.

3.2. Potential to increase the RES share

In the scenario analysis two heating systems are considered: an air-water heat pump and an electric resistance heater. This allows a comparison of the two heating systems, as shown in Figure 4. This figure shows the share of renewable energy the MPC can reach in different scenarios. An important difference can be seen when comparing the two objectives, *Min Energy* and *Max RES.* When using the *Max RES* objective, the MPC controlling the electric resistance heater can always increase the RES share when comparing it to the *Min Energy* objective, as shown in Figure 4. However, in the case of the *Max RES* objective, this increase is for the heat pump in some cases smaller and in other cases non-existent. A possible explanation for the lower performance enhancement (in terms of RES share) when using the air-water heat pump compared to the electric resistance heater in the case of the *Max RES* objective is the correlation of the heat pump COP with sunshine. Indeed, when the sun shines the outdoor temperature increases, causing a higher COP and along with that there is a higher electricity generation by solar energy. *Min Energy* therefore already receives, through the COP, indirect information about the current share of renewable energy in the case of the air-water heat pump. This reduces the potential improvement *Max RES* can make by using a signal indicating the percentage of available renewable energy on the electricity grid.

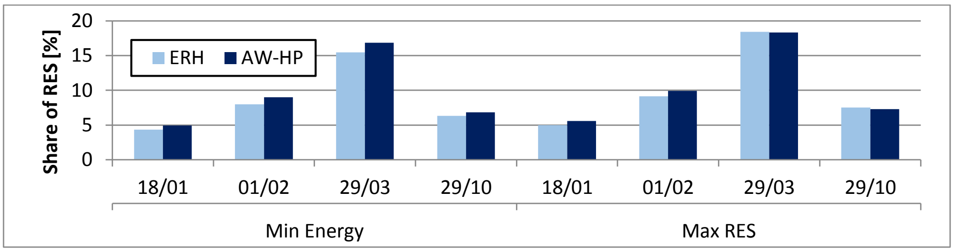

Fig. 4. Comparison of the share of RES use between the two heating systems for the different weeks in the terraced house for two MPC objectives (*Min Energy* and *Max RES*).

3.3. Estimating the primary energy factor

Figure 5 shows the PEF for different MPC objectives and periods. For the entire heating season of 2014-2015 the PEF obtained when using RBC is 2.19 and when optimising towards *Max RES* this reduces to 2.16. Two conclusions can be drawn. Firstly, the currently adopted PEF of 2.5 appears to be too high and, secondly, optimising towards *Max RES* does not bring much improvement with regard to the PEF in the current Belgian context. For completeness it should be mentioned that during this period some nuclear power plants were not running due to technical issues in Belgium. The absence of these nuclear plants, characterized by a low efficiency, has a decreasing effect on the PEF. So the lower PEF might also be (partly) caused by this fact.

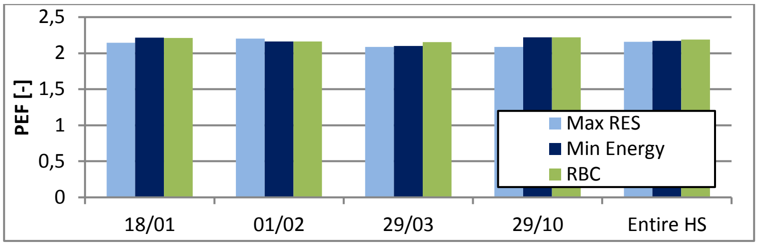

Fig. 5. The PEF for the current scenario. The MPC with objectives *Max RES* and *Min Energy* and the RBC are compared during the different periods. The heating system used is the AW-HP in the terraced house.

Considering the PEF in the future scenario with 40% of the electricity generated by RES, as shown in Figure 6, the simulations show that the PEF drops significantly, to values between 1.2 and 1.9. The large range of PEF's is due to the increase in RES share, which makes the electricity generation very dependent on meteorological conditions. These values are significantly lower than the currently adopted value of 2.5 or the values found when simulating the current scenario (as shown in Figure 5). Since buildings that are being built now, will consume electricity for the future decades, it is wrong to calculate the primary energy use with a PEF representative for the current electricity generation plants. It might be more correct and thus advisable to estimate a PEF for the lifetime of the building.

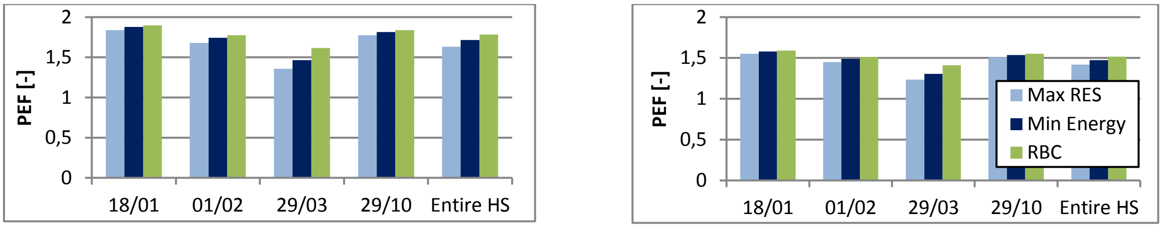

Fig. 6. The PEF for the two future scenarios, each with a different average efficiency of power plants using non-renewable energy sources. On the left an efficiency of 50% is assumed, on the right an efficiency of 60%. The different weeks are compared as well as the RBC and two MPC objectives *Max RES* and *Min Energy*. The heating system used is the AW-HP in the terraced house.

In the future scenario, the difference in PEF between the MPC using *Max RES* and the RBC can go up to 9%. This indicates a considerable difference between the smart controller and the classic RBC. Consequently, when RES are responsible for a larger share of the electricity, the primary energy use of electrical systems should be calculated with a lower PEF when they are controlled by a smart controller that optimizes renewable energy use.

3.4. Sensitivity analysis

The scenario analysis also allows investigating the influence of the different parameters of Table 2 on the potential for demand side management, which allows increasing the RES share. The impact of the type of building seems to be very limited. Aside from the fact that the detached house needs more heating, which is logical as it has a larger loss surface, no significant differences are found. A comparison of the different weeks shows that during weeks with a high electricity generation by solar energy, the MPC cannot reach a higher share of renewable energy. This can be expected as the correlation between the need for heating and sunshine is negative [25].

4. Conclusion

A smart controller, that is able to optimise towards different objectives and a classic RBC are compared for different scenarios. The variable parameters in these scenarios are: residential building type, heating system, controller, MPC objective, time period and RES share in electricity generation (where the efficiency of the non-RES electricity generation plants is also varied). The MPC, whatever the objective, clearly outperforms the RBC. Of the different objectives, minimisation to energy use and maximisation to renewable energy use are the most interesting. With the current low share of electricity originating from RES, however, the maximisation to renewable energy use does not bring any added value compared to the minimisation to energy use. This is different when the RES share on the grid increases to 40%. In these scenarios the maximisation to renewable energy use is able to increase the renewable energy use more than the total electricity use, making it an interesting candidate for demand response measures.

These results are obtained with an MPC using perfect predictions and controlling a building model, not an actual building. A following step in this research field should be the study of the influence of prediction errors. A field test should also be carried out to further analyse model mismatches and to verify the conclusions of this paper. Combinations of the objectives used here or other cost signals, such as the intraday electricity price could also be analysed.

Concerning the PEF, it appears that the currently adopted PEF of 2.5 is too high. Values for the Belgian heating season of 2014-2015 vary between 2.1 and 2.25. The PEF is thus on average lower than the currently adopted value, but it also varies through time. With 40% renewable energy on the grid, the PEF lowers to values varying between 1.2 and 1.9. In this case, the MPC maximising renewable energy use can decrease the PEF by 9% in comparison to an RBC. Therefore, in the future, the use of smart controllers could reduce the primary energy factor of the heating system, when comparing it to a system controlled by a classic controller, such as the RBC.

Acknowledgements

This study is part of the project “Towards a sustainable energy supply in cities. This project receives the support of the European Union, the European Regional Development Fund ERDF, Flanders Innovation & Entrepreneurship and the Province of Limburg. The authors would also like to acknowledge the fruitful collaboration with company VASCO and the financial support of the European Union by funding the Horizon 2020 project GEOTeCH (Grant Agreement No: 656889).

References

[1] European Commision, “Communication from the Commission to the European Parliament, the Council, the European economic and social Committee and the Committee of the Regions - A policy framework for climate and energy in the period from 2020 to 2030,” *Eur. Comm.*, p. Brussels, 2014.

[2] G. P. Henze, C. Felsmann, and G. Knabe, “Evaluation of optimal control for active and passive building thermal storage,” *Int. J. Therm. Sci.*, vol. 43, no. 2, pp. 173–183, 2004.

[3] D. Patteeuw, G. Henze, and L. Helsen, “Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits.,” *Appl. Energy*, vol. 167, pp. 80–92, 2016.

[4] A. Arteconi, D. Costola, P. Hoes, and J. L. M. Hensen, “Analysis of control strategies for thermally activated building systems under demand side management mechanisms,” *Energy Build.*, vol. 80, pp. 384–393, 2014.

[5] C. Verhelst, “Model Predictive Control of Ground Coupled Heat Pump Systems for Office Buildings,” KU Leuven, 2012.

[6] M. Sourbron, “Dynamic thermal behaviour of buildings with concrete core activation,” KULeuven, Leuven, 2012.
[7] K. Vanthournout, R. D’Hulst, D. Geysen, and G. Jacobs, “A smart domestic hot water buffer,” *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2121–2127, 2012.
[8] L. Paull, H. Li, and L. Chang, “A novel domestic electric water heater model for a multi-objective demand side management program,” *Electr. Power Syst. Res.*, vol. 80, no. 12, pp. 1446–1451, 2010.
[9] T. Ericson, “Direct load control of residential water heaters,” *Energy Policy*, vol. 37, no. 9, pp. 3502–3512, 2009.
[10] A. Moreau, “Control strategy for domestic water heaters during peak periods and its impact on the demand for electricity,” *Energy Procedia*, vol. 12, pp. 1074–1082, 2011.
[11] D. Patteeuw, C. Verhelst, and L. Helsen, “The Potential of Floor Heating in Residences as a Passive Energy Storage in a Smart Grid Context,” *CLIMA*, 2013.
[12] A. Arteconi, N. J. Hewitt, and F. Polonara, “State of the art of thermal storage for demand-side management,” *Appl. Energy*, vol. 93, pp. 371–389, 2012.
[13] C. Verhelst, D. Degrauwe, F. Logist, J. Van Impe, and L. Helsen, “Multi-objective optimal control of an air-to-water heat pump for residential heating,” *Build. Simul.*, vol. 5, no. 3, pp. 281–291, 2012.
[14] M. Vasak, A. Starcic, and A. Martinčević, “Model predictive control of heating and cooling in a family house,” *MIPRO, 2011 Proc. 34th Int. Conv.*, pp. 739–743, 2011.
[15] R. Halvgaard and N. Poulsen, “Economic model predictive control for building climate control in a smart grid,” *Innov. Smart Grid Technol. (ISGT), 2012 IEEE PES*, pp. 1–6, 2012.
[16] R. Baetens, R. De Coninck, F. Jorissen, D. Picard, L. Helsen, and D. Saelens, “OpenIDEAS – an Open Framework for Integrated District Energy Simulations,” *BS2015, 14th Conf. Int. Build. Perform. Simul. Assoc.*, pp. 347–354, 2015.
[17] D. Picard, F. Jorissen, and L. Helsen, “Methodology for obtaining linear state space building energy simulation models,” in *11th International Modelica Conference*, 2015, pp. 51–58.
[18] “openIDEAS,” *KU Leuven*. [Online]. Available: https://github.com/open-ideas. [Accessed: 01-May-2016].
[19] R. De Coninck, R. Baetens, D. Saelens, A. Woyte, and L. Helsen, “Rule-based demand-side management of domestic hot water production with heat pumps in zero energy neighbourhoods,” *J. Build. Perform. Simul.*, vol. 7, no. 4, pp. 271–288, 2014.
[20] Daikin Europe. N. V., *Technical Data Altherma ERYQ007A, EKHB007A / EKHBX007A, EKSWW150-300*. Oostende, 2006.
[21] D. Patteeuw and L. Helsen, “Residential buildings with heat pumps, a verified bottom-up model for demand side management studies,” *9th Int. Conf. Syst. Simul. Build.*, no. 1, pp. 1–19, 2014.
[22] L. Peeters, R. de Dear, J. Hensen, and W. D’haeseleer, “Thermal comfort in residential buildings: Comfort values and scales for building energy simulation,” *Appl. Energy*, vol. 86, no. 5, pp. 772–780, 2009.
[23] “Ergonomics of the thermal environment, analytical determination and interpretation of thermal comfort using the PMV and PPD indices and local thermal comfort criteria,” in *International Organisation for Standardization, ISO7730*, 2005.
[24] VASCO, *Technisch handboek Surface Heating and Cooling*. 2015.
[25] G. Reynders, T. Nuytten, and D. Saelens, “Potential of structural thermal mass for demand-side management in dwellings,” *Build. Environ.*, vol. 64, pp. 187–199, 2013.